

Workshop summary report

# Heavy Ions and New Physics

[indico.cern.ch/e/Heavy-Ions-and-New-Physics](https://indico.cern.ch/e/Heavy-Ions-and-New-Physics)

Jan Hajer

Universität Basel

Energy Frontier Workshop — Restart

# Introduction

## 2018 workshop

CP<sub>3</sub> – UCLouvain  
December 4-5 2018

*Organising Committee*  
Marco Drewes  
Andrea Giammanco  
Jan Hajer  
Fabio Maltoni

*Speakers include*  
Roderik Bruce  
Bjeter David  
David d'Enterria  
Glennys Farrar  
Oliver Gould  
Lucian Harland-Lang  
Sonia Kabana  
Simon Knäuper  
Georgios Krintiras  
Guilherme Milhano  
Swagata Mukherjee  
Jeremi Niedziela  
Jessica Priscandaro  
Valerii Pugach  
Federico Redi  
Michaela Schaumann

### HEAVY IONS AND HIDDEN SECTORS

In the recent past, several proposals have been made to search for new phenomena in heavy ion collisions at the Large Hadron Collider, e.g. axion-like particles, long-lived particles or magnetic monopoles. The objective of this workshop is to connect members of the involved communities to explore these ideas. It provides a unique opportunity for theorists, experimentalists and accelerator physicists who previously had little interaction with each other to discuss new approaches as well as practical and fundamental limitations, and to form collaborations for future research.

Registration: [agenda.irmp.ucl.ac.be/event/3186](http://agenda.irmp.ucl.ac.be/event/3186)

## Goals

### Exploration of New Physics searches in heavy ion collisions

#### First workshop resulted in

### contribution to 'European Strategy for Particle Physics' (ESPP)

#### New physics searches with heavy-ion collisions at the CERN Large Hadron Collider

Roderik Bruce<sup>1</sup>, David d'Enterria<sup>2,18</sup>, Albert de Roeck<sup>2</sup>, Marco Drewes<sup>3</sup>, Glennys R Farrar<sup>4</sup>, Andrea Giammanco<sup>5</sup>, Oliver Gould<sup>5</sup>, Jan Hajer<sup>3,6</sup>, Lucian Harland-Lang<sup>8</sup>, Jan Heisig<sup>2</sup>, John M Jowett<sup>10</sup>, Sonia Kabana<sup>7</sup>, Georgios K Krintiras<sup>3,17</sup>, Michael Korsmeier<sup>8,9,10</sup>, Michele Lucente<sup>3</sup>, Guilherme Milhano<sup>11,12</sup>, Swagata Mukherjee<sup>13</sup>, Jeremi Niedziela<sup>7</sup>, Vitalii A Okorokov<sup>14</sup>, Arttu Rajantie<sup>15</sup> and Michaela Schaumann<sup>16</sup>

J. Phys. G 47 (2020) 6, 060501  
e-print: 1812.07688 [hep-ph]

In the process of formulating a contribution to Snowmass 2021

## 2021 workshop

ECT\*  
FONDAZIONE  
EUROPEO KESLER

ONLINE Workshop  
**STRONG**  
2020

### Heavy Ions and New Physics

May 20-21, 2021 on ZOOM Platform

**Abstract / Main Topics**  
In the recent past, several proposals have been made to exploit heavy ion collisions at the Large Hadron Collider (LHC) to search for new phenomena in particle physics, including axion-like particles, long-lived particles beyond the Standard Model and magnetic monopoles. The objective of this workshop is to bring together members of the involved communities to exploit the potential of these ideas, either during scheduled LHC runs or in dedicated efforts at the LHC or future colliders. We want to create a unique opportunity for exchange between scientists working in different fields of experimental physics, theoretical physics, accelerator physics and detector physics that otherwise have little connection.

**Keynote speakers**  
Elena-Bianca Albino<sup>1</sup> – Roderik Bruce<sup>2</sup> (CERN) – Emilianio Csanosi<sup>3</sup> (CERN) – Hisham Elzein<sup>4</sup> (Fudan University) – Glennys Farrar<sup>5</sup> (MIT) – Oliver Gould<sup>6</sup> (Liverpool University) – Taku Goto<sup>7</sup> (Tokyo University) – Lucian Harland-Lang<sup>8</sup> (Oxford University) – Yen-Jie Lee<sup>9</sup> (Massachusetts Institute of Technology) – Tanguy Pèguet<sup>10</sup> (IAP) – James Prell<sup>11</sup> (Alberta University) – Arttu Rajantie<sup>12</sup> (Imperial College) – Swagata Mukherjee<sup>13</sup> (University of Hamburg) – Vitalii A Okorokov<sup>14</sup> (Hamburg University) – Aditya Uzun<sup>15</sup> (Nagasaki University) – Susanne Westhoff<sup>16</sup> (Heidelberg University)

**Program**

**Organizers**  
Marco Drewes<sup>1</sup> (UCLouvain), David d'Enterria<sup>2</sup> (CERN), Andrea Giammanco<sup>3</sup> (UCLouvain), Jan Hajer<sup>4</sup> (Bosch University)

\* This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101019718.

Workshop of the ECT\* Program Grant A4011 The ECT\* is part of the Fondazione Bruno Kessler. The Centre is funded by the Italian Government, the Trentino-South Tyrol Region, the Province of Trento, the Autonomous Province of Trento, the University of Trento, the INFN TIFPA and has the support of the Department of Physics of the University of Trento.

# Magnetic monopoles

Magnetic field in 5.02 TeV PbPb

$$|B| \simeq 4 \cdot 10^{16} \text{ T} \simeq 7 \text{ GeV}^2$$

Magnetic charges

$$\nabla \cdot E = \rho_E, \quad \nabla \times E = -\partial_t B - j_M$$

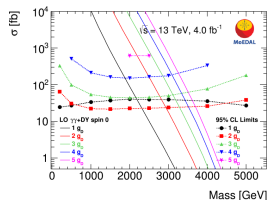
$$\nabla \cdot B = \rho_M, \quad \nabla \times B = -\partial_t E - j_E$$

Dirac quantisation

$$g \in g_D \mathbb{Z} \text{ with } g_D = 2\pi/e_0$$

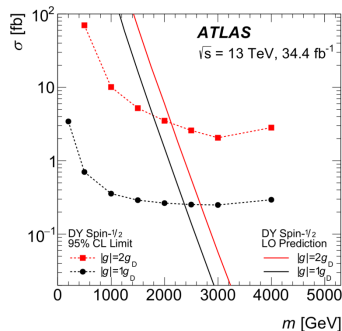
MoEDAL

2019



ATLAS

2019



Drell-Yan crosssection is wrong

$$e \rightarrow g = 2\pi/e$$

Duality

Because  $g_D \approx 20.7 \gg 1$

Process is non-perturbative

Instanton tunneling action

$$\Gamma \propto e^{-S_{\text{inst}}}$$

Monopole Schwinger production

$$\Gamma = \frac{g^2 |B|^2}{8\pi^3} \exp\left(\frac{g^2}{4} - \frac{\pi m^2}{g|B|}\right)$$

Needs strong magnetic field

Time dependence

enhanced production for rapid pulses

Spatial inhomogeneity

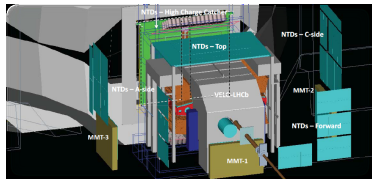
Effect not known

Solitonic monopole size

Enhances production

# Magnetic monopoles in MoEDAL

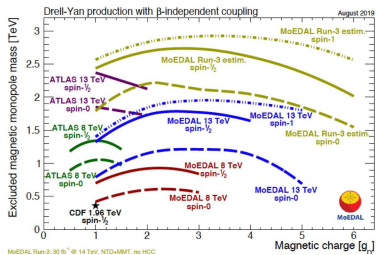
## MoEDAL close to LHCb



## Physics potential

- Magnetic monopoles
- Multiply charged particles
- Long-lived particles
- Mini charged particles
- Q-balls
- Strangelets
- Highly ionizing particles

## Magnetic monopoles in $pp$ 2019



## Leading limits

$$1.5 \text{ TeV} < m < 3.75 \text{ TeV}$$

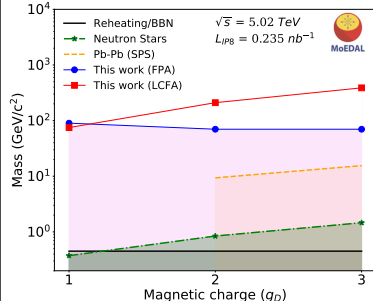
$$2g_D < g < 5g_D$$

Only photon fusion and Drell-Yan

No non-perturbative effects

## Magnetic monopoles in PbPb

New result: 2106.11933  
Includes Schwinger production



Exclusion of masses up to 75 GeV

# New Physics @ CMS

Magnetic monopoles  
under investigation

Signature considerations

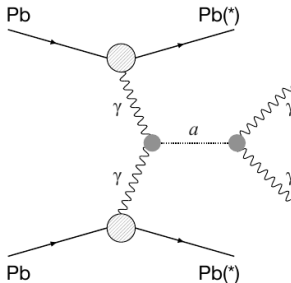
Non-helicoidal trajectory  
Heavily ionising  
Specific shower shape  
If monopolium: decay to  $\gamma\gamma$

Naive estimate for PbPb  
using Superchic3  
only large clusters in tracker  
no systematic uncertainties  
 $M \sim 400 \text{ GeV}$  @ 95 % CL

Axion like particles (ALPs)  
light pseudoscalar

Often studied via  $\gamma\gamma$  interaction

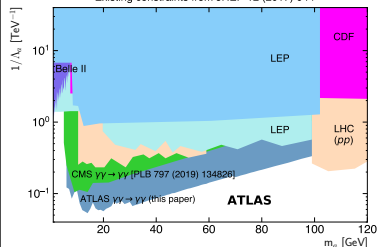
Ultra peripheral HI collisions



Best ALPs limits

$5 \text{ GeV} < m < 6 \text{ GeV}$

Existing constraints from JHEP 12 (2017) 044



Cuts

$E_T > 2 \text{ GeV}$

$|\eta| < 2.4$

$m_{\gamma\gamma} > 5 \text{ GeV}$

$p_T < 1 \text{ GeV}$

$A_\phi = |1 - \Delta\phi/\pi| < 0.01$

# ALPs @ ATLAS

## Search strategy

exactly two photons with  
 $E_T > 2.5 \text{ GeV}$  and  $|\eta| < 2.37$

invariant mass  $m_{\gamma\gamma} > 5 \text{ GeV}$

## Veto

no tracks with  $p_T > 100 \text{ MeV}$

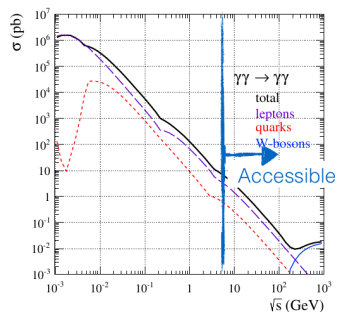
no pixel tracks with  
 $p_T > 50 \text{ MeV}$  and  $|\eta_{t\gamma}| < 0.5$

## Back-to-back topology

$p_T(\gamma\gamma) < 2 \text{ GeV}$   
reduced acoplanarity  $< 0.01$

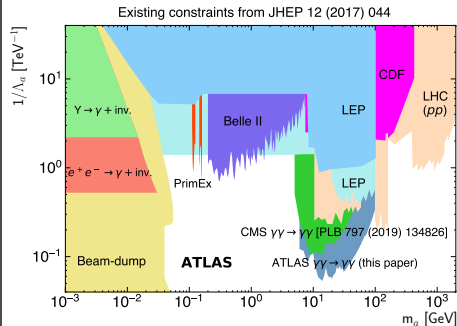
Partially exploits low trigger

## Cross section steeply falling



## Exclusion with $2.2 \text{ nb}^{-1}$

2021



# ALPs @ LHCb

## Study used

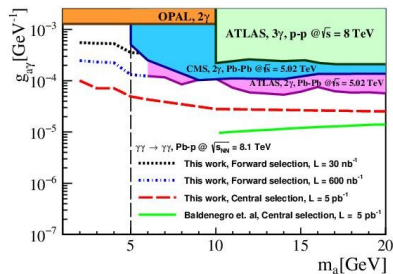
- Superchic3
- FPMC (modified for PbPb)

## Acceptances included

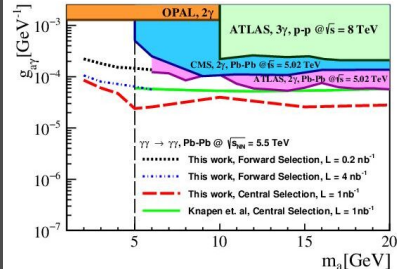
## Main backgrounds

- light-by-light scattering
- di-electron with mis-identification

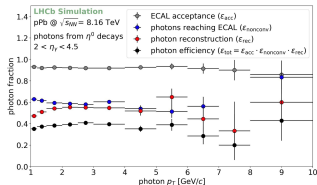
## $p\text{Pb}$



## PbPb



## Photon reconstruction in $p\text{Pb}$



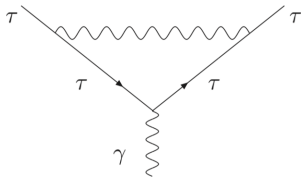
Expected to surpass current limits  
for masses below 5 GeV

Light ALPs also accessible @ ALICE  
Potential New Physics search with-  
out competition by CMS or ATLAS

# $\tau$ -lepton $g - 2$

anomalous magnetic moment

$$a_\tau = (g_\tau - 2)/2$$

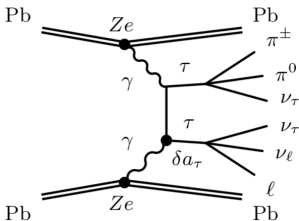


Constraint from DELPHI

$$-0.052 < a_\tau < 0.013$$

poorly constrained due to short lifetime

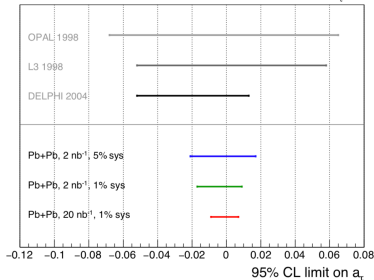
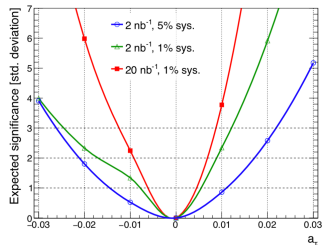
Measure in HI



Differential distribution

Cancel uncertainties using  
ratio to  $ee$ ,  $\mu\mu$  processes

Expected improvement





# Sexaquarks

$$S = uud\bar{d}s\bar{s}$$

spin, colour, and flavour singlet

$$m_S \approx 2m_p \quad B = -2$$

$$Q = 0 \quad S = -2$$

no pion interactions

Tightly bound and compact

$$r_S \approx 0.2 \text{ fm}$$

Dark matter candidate

Quasi stable with  $\Omega_{\text{DM}}/\Omega_b \approx 5$   
without free parameters

So far not excluded

Despite searches for the  $H$ -dibaryon with same quark content

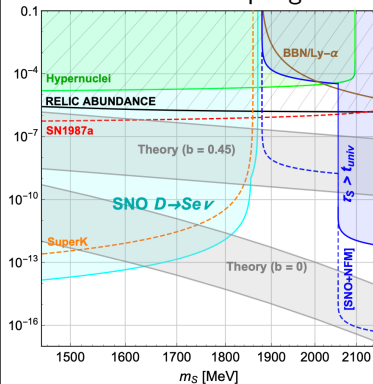
Because search relies on

- unstable particle
- heavy particle ( $> 2 \text{ GeV}$ )
- interaction with  $\Lambda$

However

$S$  is similar to neutron

Exclusion bounds on  $S \rightarrow \Lambda\Lambda$   
effective Yukawa coupling

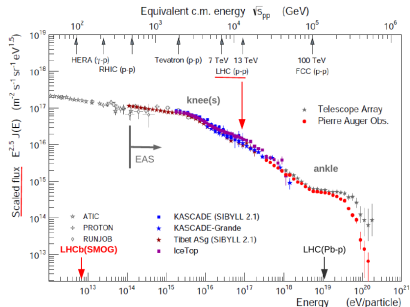


Proposal

search in HI collisions  
behind a neutron absorber shield

# Muon deficit in cosmic rays just above LHC energies

## Cosmic ray energy spectrum



## Described by

- string fragmentation
- high density effects in hadronization
- diffraction
- higher order effects (multi-Pomerons)
- remnants

## Muon production

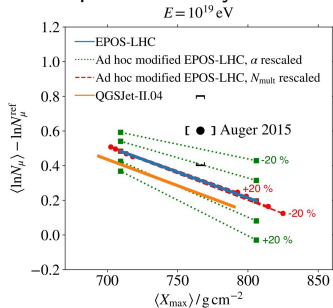
in air showers badly described

## Muon deficit

in simulations

## Ad hoc change of

muon production by  $\sim +4\%$



uncertainties mostly due to

nuclear collision extrapolations

Need input

from light ion collisions data

Precision measurements in

pA and AA with  $A < 20$  needed

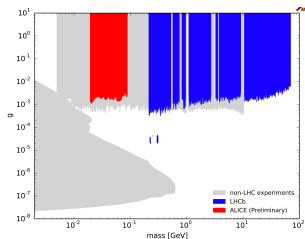
Ideal test

pO and OO collisions

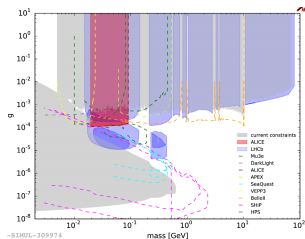
Although LHC results suggest that the muon deficit problem is due to SM uncertainties there is room for NP models

# New Physics @ ALICE

## Dark photon search Run 1

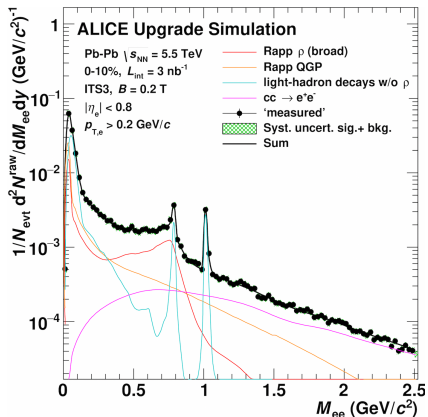


## Projection Run 3 and 4



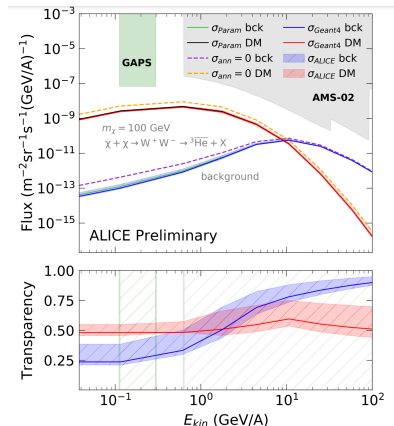
## GeV scale dark boson under study

### QGP is additional thermal source



ALI-SIMUL-306860

## anti- $^3\text{He}$ cosmic ray predictions



ALI-PREL-486179

# Conclusion

- Second successful workshop on New Physics searches in heavy ion collisions
- Potential New Physics (more than presented in this talk)
  - Magnetic monopoles
  - Axion-like particles
  - Sexaquarks
  - Dark photons
  - Soft New Physics
  - Long-lived New Physics
- Connection to
  - Cosmic ray air showers
  - $\tau$ -lepton  $g - 2$
  - Gravitational waves
- Summary will be published as contribution to Snowmass 2021

# Appendix

# Upcoming HI runs at the LHC

## PbPb and pPb in Run 3 and 4

more collisions at LHCb  
minor penalty for the others

## 1-month PbPb

$2.2\text{--}2.8\text{ nb}^{-1}$  ATLAS/ALICE/CMS  
 $\sim 0.5\text{ nb}^{-1}$  LHCb

$\sim 5$  runs to reach targets

$13\text{ nb}^{-1}$  IP<sub>1/2/5</sub>  
 $2\text{ nb}^{-1}$  IP<sub>8</sub>

## Future work

performance enhancements studies

## 1-month pPb

$530\text{--}690\text{ nb}^{-1}$  ATLAS/CMS  
 $310\text{ nb}^{-1}$  ALICE  
 $150\text{ nb}^{-1}$  LHCb

## Two runs sufficient

$1200\text{ nb}^{-1}$  IP<sub>1/5</sub>  
 $600\text{ nb}^{-1}$  IP<sub>2</sub>  
factor  $\sim 2$  missing LHCb

## Beam loss mitigation

Orbit bumps  
Crystal collimators  
(Dispersion suppressor collimators)

## Options for short light ion run

with OO and pO

## Motivation

physics interest  
machine performance study for future light-ion operation

## Run 5

Updated scenarios for light-ion operation under study

# The SuperChic Monte Carlo event generator

Ultraperipheral HI collisions

$\gamma\gamma$  collisions key mode for BSM production

SuperChic 4 MC

full differential generator

Central exclusive processes (CEP)

- QCD induced
- photon induced

including survival factor for  $pp$ ,  $pA$ , and  $AA$

Examples

- $\tau$ -lepton  $g - 2$
- ALPs and light-by-light scat.
- Monopoles

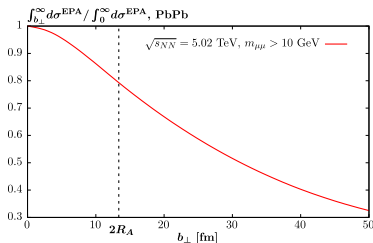
Basic idea

$$\sigma = \int dx_1 dx_2 n_1 n_2 \hat{\sigma}_{\gamma\gamma \rightarrow X}$$

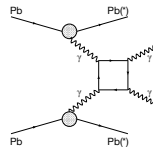
Photon flux  $n_i$  well known  
in terms of EM form factor

Survival factor captures  
additional soft production

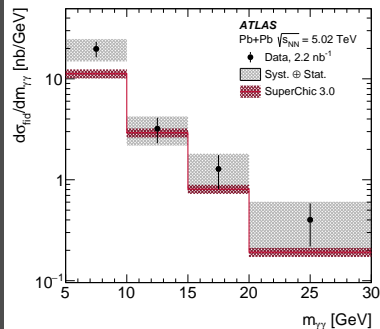
impact parameter dependence



ALPs @ ATLAS



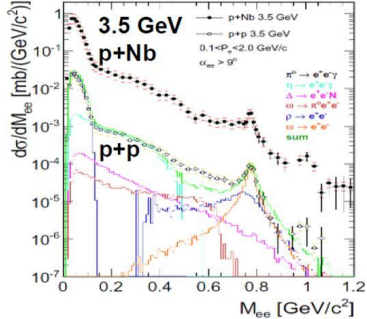
Good agreement with data



# Light dark photons from meson decays

HADES

GSI SIS18 detector in Darmstadt



$pp$  at 3.5 GeV  
 $pNb$  at 3.5 GeV  
Ar KCl at 1.76A GeV

Theoretical description

with Parton Hadron String Dynamics (PHSD)  
a non-equilibrium microscopic transport approach

Production of dark photons

in Dalitz decays

- $\pi^0, \eta \rightarrow \gamma\gamma_{\text{dark}}$
- $\Delta \rightarrow N\gamma_{\text{dark}}$

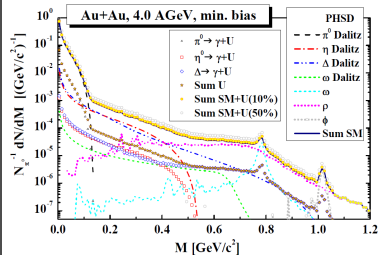
Decay into lepton pair

$$\gamma_{\text{dark}} \rightarrow e^+e^-$$

Described approach

allows flexible reinterpretation of experimental constraints

Predictions w/o exp. acceptance



Reproduce

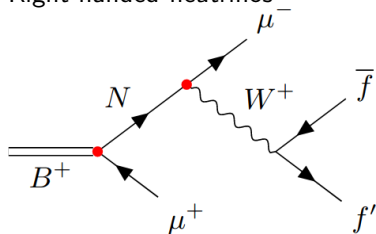
upper limit on kinetic mixing  
for  $0.15 \text{ GeV} < m_{\gamma_{\text{dark}}} < 0.4 \text{ GeV}$



# Soft New Physics

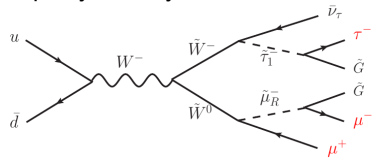
## GeV-scale New Physics

### Right-handed neutrinos

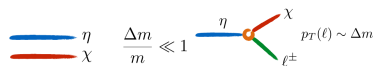


### cascade decay

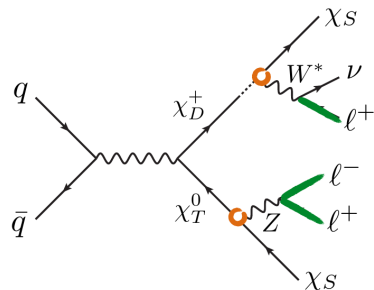
### supersymmetry



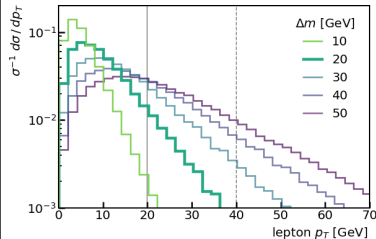
## compressed dark sectors



## Concrete DM model signature



## Not detectable in $pp$



## Idea: Soft leptons in HI

Higher Sensitivity due to lower trigger

# Soft long-lived particles

Light right-handed neutrinos

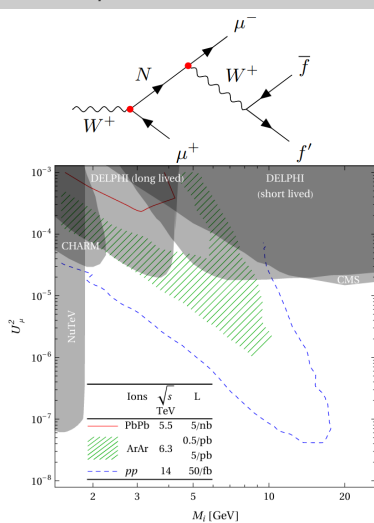
long-lived  
escape QGP unhindered

Ideas for searches

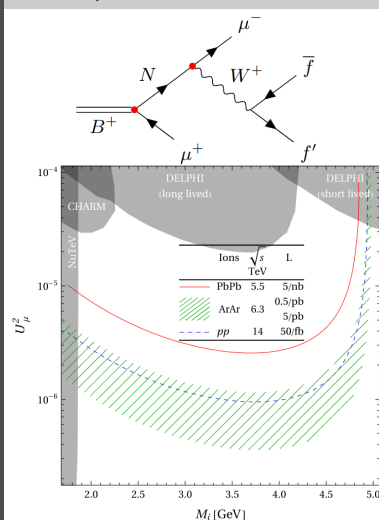
- exploit low triggers
- use lighter ions

Lighter ions can have advantage  
over  $pp$  collisions at equal running  
time

$$W^\pm \rightarrow \mu^\pm N$$



$$B^\pm \rightarrow \mu^\pm N$$



# New particle observations in PbPb @ CMS

$X(3872)$  resonance

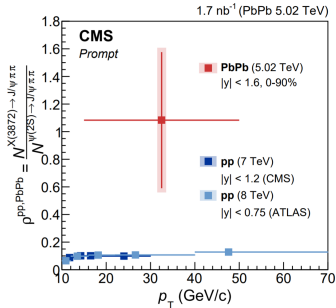
exotic meson with  $1^{++}$

Possible explanations

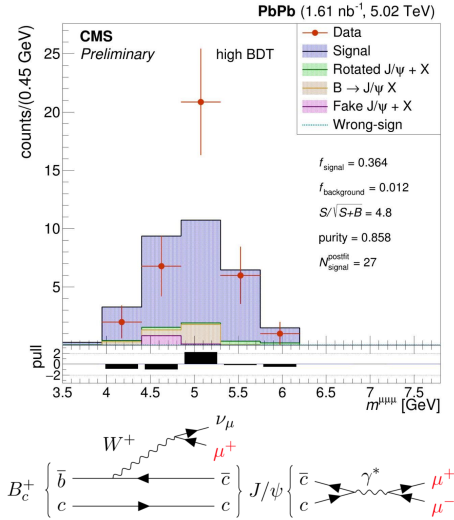
$cucu$  Tetraquark

$D^0-\bar{D}^{*0}$  molecule

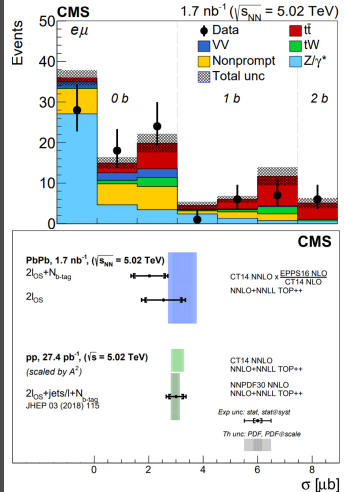
$X(3872)$  to  $\psi(2S)$  yield ratio



$B_c$  in PbPb well above  $5\sigma$



$t\bar{t}$  production



# Potential heavy New Physics in cosmic rays

Air showers

QCD interactions under extrem conditions

Interaction energy

considerably above LHC energy

Muon deficit problem

Air shower simulation produce much fewer muons for showers above  $10^7$  GeV

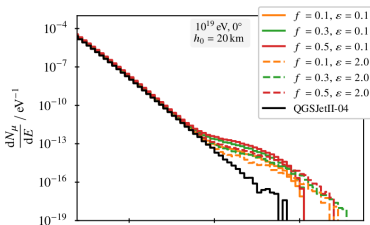
Idea: Heavy New Physics

that produces many muons

CORSIKA8

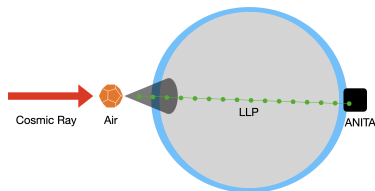
Framework for investigations of particle cascades in astroparticle physics

Simulation of New Physics models



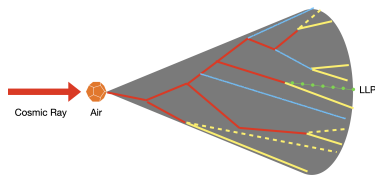
is able to explain the muon deficit problem

Can be linked to



ANITA excess

Connected to



long-lived particle searches in cosmic ray air showers

# CASTOR Calorimeter @ CMS

Very forward calorimeter

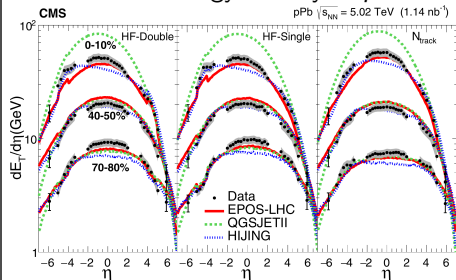
Successful data taking  
in Run 1 and 2

Unique calorimeter data

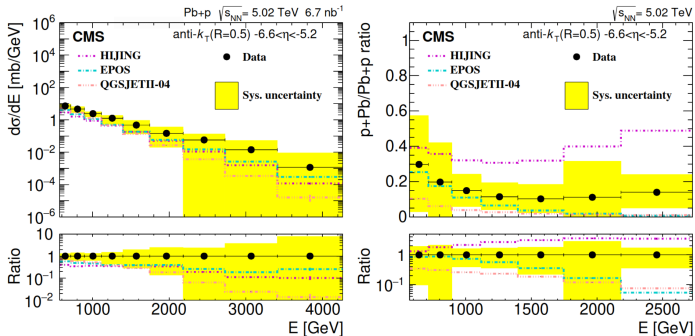
$$-6.6 < \eta < -5.2$$

Centrality and pseudorapidity dependence

of transverse energy density in  $p\text{Pb}$



Inclusive very forward jet cross sections in  $p\text{Pb}$



Potential studies of New Physics

Baryon-rich forward fragmentation region  
search for strangelets and penetrating particles

# Gravitational Waves

Proposal to test

mHz gravitational waves at LHC

Method

Change in bunch travel time due to change in test mass velocity

Velocity change causes

significant effect on travel time

LHC

used as storage ring

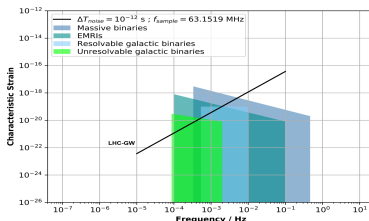
Needs additional

detection system

Noise sources

- Quantum noise (quantum uncertainty in time-tagging proton bunches)
- Gravity gradient noise (due to sun, moon, alps, ...)
- Seismic noise
- Radio frequency phase noise

Sensitivity



Idea

Probe gravitational waves during heavy ion runs

Questions

Effect of rest gas collisions

Effect of synchrotron radiation

Impact of lower energy